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RESPONSE OF INTERMEDIATE SCALE SUBMARINE MODELS TO SIMULATED NUCLEAR UNDERWATER EXPLOSIONS

Volume I - Development of Computational Procedures

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12 June 1981

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The physical significance of the terms in the Doubly Asymptotic Approximation (DAA) are evaluated. Additionally, the computational aspects of the terms are discussed. Two simplified versions of the DAA are proposed. These versions are referred to as the Plan Wave-Added Mass (PWAM) cylinder approximation and the PWAM plate approximation. Both approaches are evaluated via comparison to exact solutions and full DAA solutions. The PWAM plate approximation is shown to give results almost identical to the full DAA for problems dominated by structural

20. ABSTRACT (Continued)

deformation. Both methods appear to do a good job of picking up shell translation response.

PREFACE

This report is Volume I of a two-volume report summarizing work performed by Pacifica Technology under contract DNA 001-80-C-0048 with the Defense Nuclear Agency. Volume I describes the theoretical development and evaluation of computational efficient approaches for the analysis of shock wave induced deformations in submerged structures. Volume II demonstrates the application of these techniques to the ISM-A4 experiment. Contract monitor for this study was LT Dennis Sobota, USN.

Table 1. Conversion factors for U.S. customary to metric (SI) units of measurement.

To Convert From	To	Multiply By
angstrom	meters (m)	1.000 000 X E -10
atmosphere (normal)	kilo pascal (kPa)	1.013 25 X E +2
bar	kilo pascal (kPa)	1.000 000 X E +2
barn	meter^2 (m^2)	1.000 000 X E -28
British thermal unit (thermochemical)	joule (J)	1.054 350 X E +3
calorie (thermochemical)	joule (J)	4.184 000
cal (thermochemical)/cm^2	mega joule/m^2 (MJ/m^2)	4.184 000 X E -2
curie	*giga becquerel (GBq)	3.700 000 X E +1
degree (angle)	radian (rad)	1.745 329 X E -2
degree Fahrenheit	degree kelvin (K)	t_K = (t°f + 459.67)/1.8
electron volt	joule (J)	1.602 19 X E -19
erg	joule (J)	1.000 000 X E -7
erg/second	watt (W)	1.000 000 X E -7
foot	meter (m)	3.048 000 X E -1
foot-pound-force	joule (J)	1.355 818
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 X E -3
inch	meter (m)	2.540 000 X E -2
jerk	joule (J)	1.000 000 X E +9
joule/kilogram (J/kg) (radiation dose absorbed)	Gray (Gy)	1.000 000
kilotons	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 X E +3
kip/inch^2 (ksi)	kilo pascal (kPa)	6.894 757 X E +3
ktap	newton-second/m^2 (N-s/m^2)	1.000 000 X E +2
micron	meter (m)	1.000 000 X E -6
mil	meter (m)	2.540 000 X E -5
mile (international)	meter (m)	1.609 344 X E +3
ounce	kilogram (kg)	2.834 952 X E -2
pound-force (lbs avoirdupois)	newton (N)	4.448 222
pound-force inch	newton-meter (N·m)	1.129 848 X E -1
pound-force/inch	newton/meter (N/m)	1.751 268 X E +2
pound-force/foot^2	kilo pascal (kPa)	4.788 026 X E -2
pound-force/inch^2 (psi)	kilo pascal (kPa)	6.894 757
pound-mass (lbm avoirdupois)	kilogram (kg)	4.535 924 X E -1
pound-mass-foot^2 (moment of inertia)	kilogram-meter^2 (kg·m^2)	4.214 011 X E -2
pound-mass/foot^3	kilogram/meter^3 (kg/m^3)	1.601 846 X E +1
rad (radiation dose absorbed)	**Gray (Gy)	1.000 000 X E -2
roentgen	coulomb/kilogram (C/kg)	2.579 760 X E -4
shake	second (s)	1.000 000 X E -8
slug	kilogram (kg)	1.459 390 X E +1
torr (mm Hg, 0° C)	kilo pascal (kPa)	1.333 22 X E -1

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (Gy) is the SI unit of absorbed radiation.

A more complete listing of conversions may be found in "Metric Practice Guide E 380-74," American Society for Testing and Materials.

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LIST OF ILLUSTRATIONS

1. INTRODUCTION

During the past decade great strides have been made in developing computational techniques for evaluating the transient response of submerged structures to non-harmonic loadings. The Doubly Asymptotic Approximation (DAA) developed independently by Geers [1]* and Mnev and Pertsev [2] has become widely accepted as the best compromise between accuracy and computational efficiency of the various theories proposed. Since its initial development, active research on the DAA has been pursued in three distinct areas: theoretical evaluation and improvement, computational implementation, and comparison with exact solutions and experimental data. The work detailed in this report covers results of efforts in all three of the above areas.

Initially our work was to encompass two separate tasks. The first of these tasks was the development of simplified theories for implementing DAA calculations of submerged structure shock response. While the DAA has proven to be a very effective tool, certain characteristics of its computational implementation severely limit its application to real structural configurations. The second task was to perform pre-test predictions for the ISM-A4 test. The ISM-A4 test was a test designed to produce moderate structural damage to an Intermediate Scale Model (ISM) submarine structure submerged in water and exposed to simulated nuclear explosion loading. The ISM-A4 test was designed as a follow-up to the ISM-A3 test. Its purpose was to examine the sensitivity to load variations of the deformation pattern in an ISM model. While we had not performed pre-test predictions on the ISM-A3 test, we had performed a post-test study of the sensitivity of the model to variations in material properties and magnitudes of the plateau pressure loading [3]. The study of [3] utilized a quarter model idealization of the ISM structure. As part of the PacTech ISM-A3 quarter model study, a mesh convergence study was undertaken. The results of the quarter model mesh convergence study were used as a baseline in developing a structural model for the ISM-A4 analysis. Based on this, it was apparent that an effective structural mesh would require approximately 1,000 wet quadrilateral shell elements for the cylindrical shell and end plates.

*Numbers in brackets refer to references listed at the end of text.

Our initial plans were to utilize the USA-STAGS [4,5,6] computer code for the ISM-A4 analysis. This code combination was used for the ISM-A3 quarter model study and proved to be very effective. One restriction of the USA code is that on a CDC CYBER 176 computer such as that utilized by the Defense Nuclear Agency (DNA), the maximum number of fluid elements is limited to 216. This limit is caused by the form of the DAA equations [7]. The added mass matrix in the DAA is a full matrix. If in-core operations such as those coded into the USA code are performed, severe size restrictions are imposed on equation systems involving full matrices. For the ISM-A3 quarter model study the restriction to less than 216 fluid elements was no problem since the structural mesh contained 156 elements on its wet surface. Thus for the quarter model study a one-to-one overlay of structural and fluid elements was achieved without the necessity of modifying the USA code.

Figure 1 shows a plot of the mesh developed for the ISM-A4 analysis. The cylindrical shell is subdivided into 22 elements axially and 32 circumferentially. Each end plate has 3 rings of 32 elements. The complete model thus contains 896 elements in contact with the fluid mesh. If USA were to be used for the fluid analysis of the ISM-A4, a one-to-one overlay of fluid and structure elements could not be achieved. Thus, the following choices were available for analyzing the ISM-A4 test:

1. Using the USA-STAGS code combination, develop a 216 element fluid mesh with fluid elements overlaying more than one structural element to cover the 896 element structural mesh.

2. Reduce the structural mesh size to 216 elements.

3. Modify the USA code to handle more than 216 elements in the fluid mesh.

4. Implement a modified fluid-structure interaction formulation in conjunction with the STAGS structural analysis code. The modified fluid-structure interaction formulation should be one which does not have the mesh restrictions associated with the DAA added mass matrix.

The first option, which has been recommended by other groups [8] was rejected for the current problem. It is important to note that the fluid mesh determines the form of the pressure variation over the structure. An average pressure is calculated for each fluid element. This average pressure is then applied to each structural element contained in the projection of the

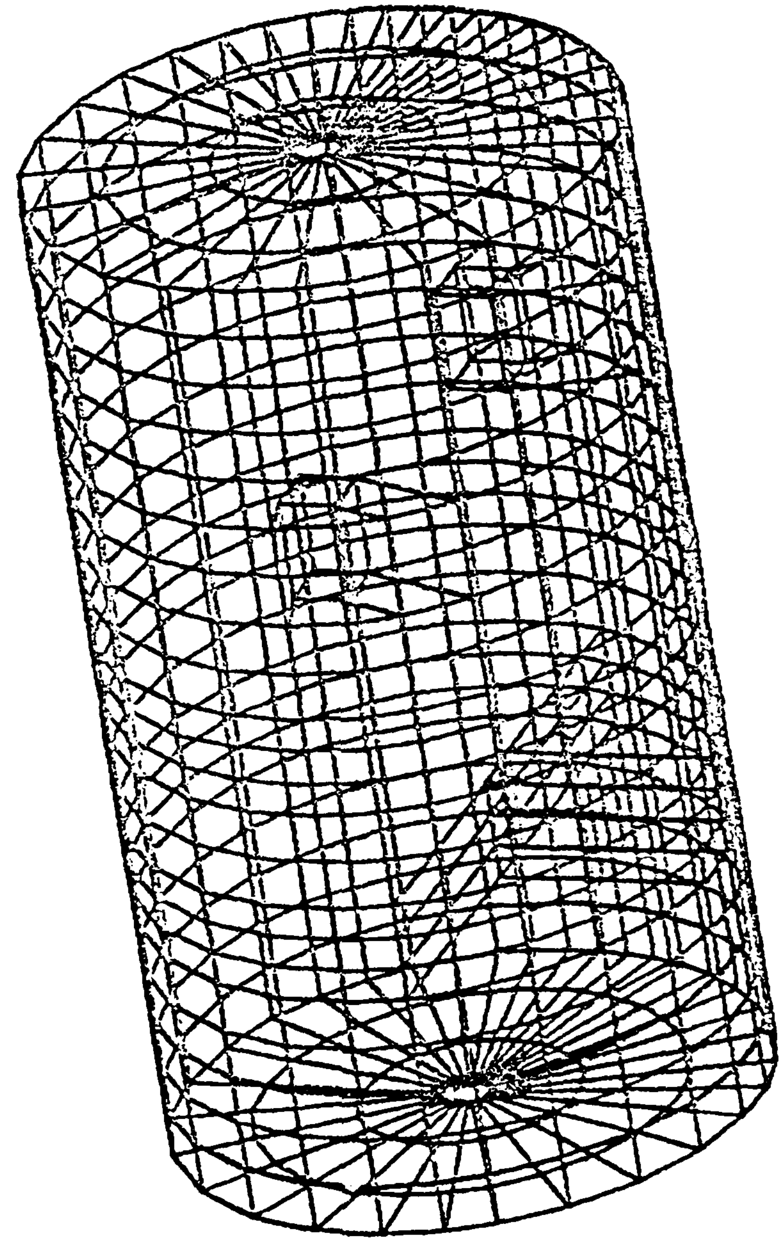

Figure 1. STAGS Mesh for ISM Analysis

fluid mesh onto the structural mesh. Since we are concerned with nuclear type (engulfment) loadings, significant pressures and associated structural response is occurring over the entire structure. Thus, there is no region of the structure in which spreading an average pressure rather than applying the localized pressure distribution will not lead to an erroneous structural response mode. Option 2. above was rejected immediately since it would require violating all of the criteria developed in the mesh convergence study of [3]. The possibility of modifying the USA code, option 3., was considered in some detail. As was mentioned, the mesh restrictions arise from the combination of in-core matrix operations and the full nature of the added mass matrix in the DAA equations. If an out-of-core matrix decomposition, multiplication, and back substitution option were included in USA, the mesh restrictions would vanish. The penalty associated with this approach is a large increase in the computer I/O charges associated with the matrix multiplications and back substitutions at each time step. For a 1,000 element mesh this approach might be feasible, but for anything larger the computer costs would quickly become prohibitive. Since the ISM is a relatively small structure, and since accurate structural modeling of larger, more complex structures might entail structural meshes of more than 10,000 elements, this option was dropped in favor of the approach in option 4.

As was previously mentioned, our work was initially split into two phases. When an accurate and efficient USA-STAGS analysis of the ISM-A4 test was shown to be infeasible, a decision was made to merge the two tasks. The development of the simplified DAA approach which resulted and was used for the ISM-A4 analysis is discussed in Chapter 2 of this report. Chapter 3 provides an evaluation of the accuracy of the new method for two-dimensional problems. The actual application of this new method to the prediction of the ISM-A4 experiment is presented in Volume II of this report.

2. DEVELOPMENT OF SIMPLIFIED DAA

Before discussing reformulations of the DAA, we will review the basic development of the DAA and attempt to put the various terms in the DAA equation into a proper physical context. The basic equation of the DAA for the scattered pressure in the fluid is

$$\underline{\underline{A}}\,\dot{\underline{p}}_s + \rho c\,\underline{\underline{A}}\,\underline{\underline{M}}_f^{-1}\,\underline{\underline{A}}\,\underline{p}_s = \rho c \underline{\underline{A}}\,(\ddot{\underline{x}}-\dot{\underline{u}}_i) \qquad (2\text{-}1)$$

where,

- $\underline{\underline{A}}$ = diagonal matrix of associated nodal point areas multiplied by the dot product of the shell normal vector and local solution degree of freedom base vector
- $\underline{p}_s$ = vector of nodal point scattered pressures
- ρ = fluid mass density
- c = fluid acoustic wave speed
- $\underline{\underline{M}}_f$ = fluid added mass matrix
- $\underline{x}$ = vector of structural nodal point generalized displacements
- $\underline{u}_i$ = vector of fluid particle velocity vector components associated with incident pressure wave.

For simplicity, equation (2-1) will be considered in conjunction with the equation for an undamped, linearly elastic structure restricted to small displacements,

$$\underline{\underline{M}}\,\ddot{\underline{x}} + \underline{\underline{K}}\,\underline{x} = -\underline{\underline{A}}\,(\underline{p}_i+\underline{p}_s) \qquad (2\text{-}2)$$

where,

- $\underline{\underline{M}}$ = structural mass matrix
- $\underline{\underline{K}}$ = structural stiffness matrix
- $\underline{p}_i$ = vector of nodal point incident pressures.

Equation (2-1) represents the standard form of the DAA. A more complex form is actually implemented in USA, however, its fundamental nature is unchanged.

To understand the physical significance of the various terms in equation (2-1), we will now review the basic development of the DAA.

As its name would imply, the Doubly Asymptotic Approximation is a combination of two limiting case solutions to the fluid-structure interaction problem. Consider first the case of an acoustic, planar shock wave impinging normal to a rigid flat surface. If p_I and u_I represent the incident pressure and normal component of the fluid particle velocity, the rigid body scattered pressure p_s is given by

$$p_s = \rho\, c\, u_I \tag{2-3}$$

Equation (2-3) is exact in the acoustic limit for planar structures and plane incident wave fronts. In practice, equation (2-3) can be used with reasonable accuracy provided the radius of curvature of the incident wave is much larger than the radius of curvature of the structure it is incident upon. In addition, the curvature must be small enough that refraction of the incident wave around the structure is negligible. If the structure moves due to the impact of the incident wave, equation (2-3) takes the form

$$p_s = -\rho c\, (\underset{\sim}{n} \cdot \underset{\sim}{u}_I - \underset{\sim}{n} \cdot \dot{\underset{\sim}{x}}), \tag{2-4}$$

where $\underset{\sim}{n}$ is the outward normal vector on the surface of the structure. Equation (2-4) can be seen to consist of two components, the pressure due to the reflection of the incident wave and the pressure due to the motion of the structure against the fluid surface. The net effect of the two components is a scattered pressure wave in phase with the structural velocity and whose magnitude is proportional to the velocity of the structure relative to the incident wave. Equation (2-4) is valid in the acoustic regime ($p_I < 5{,}000$ psi) and for very early time response. The early time restriction is predicated by the local nature of equation (2-4). The relationship defined by equation (2-4) is referred to in the literature as the "Plane Wave Approximation" (PWA) and was used extensively in the 1950's and early 1960's before the availability of large-scale computers. As was mentioned, the PWA assumes the scattered pressure at a point to be in phase with and completely specified by the structural velocity at that point. Hence it is accurate only during the impulsive response phase of the problem and when global structural stiffness begins to control the response, the PWA loses accuracy rapidly.

At late times, the fluid structure system is assumed to vibrate in its lowest frequencies and corresponding mode shapes. It is assumed that the structural velocities in these modes are small compared to the particle velocities in the incident wave. In reference [9] it was shown that for long wavelength acoustic fluid-structure interaction, the fluid response asymptotically approaches incompressible, inviscid flow. The physical basis for this assumption is that the fluid around the structure moves in phase with the structures motion without being compressed. This type of fluid structure analysis is referred to as the "Virtual (Added) Mass Approximation" (VMA), and has been used by Chertock [10] and Hicks [11] for calculating the late time flexural response of ships and submarines. In a general matrix form, the VMA can be written

$$\underline{\underline{A}}\, p_s = \underline{\underline{M}}_f\, \underline{\ddot{x}}. \tag{2-5}$$

As opposed to the PWA [equation (2-4)], the VMA is seen to couple the global structural response to the local scattered pressure. In addition, the pressure in the VMA is in phase with the structural acceleration and hence displacement harmonics, whereas the pressure in the PWA is out of phase with the structural displacement.

In the DAA, the early time asymptote, PWA, and the late time asymptote, VMA, are coupled together via their relationship to the structural motion. This is accomplished by rewriting equation (2-4) in matrix notation as

$$\underline{\underline{A}}\, \underline{p}_s = -\rho c\, \underline{\underline{A}}\, (\underline{u}_I - \underline{\dot{x}}). \tag{2-6}$$

After differentiating equation (2-6) and suitable manipulations the two asymptotic equations can be equated to give

$$\underline{\underline{A}}\, \underline{\dot{p}}_s + \rho c\, \underline{\underline{A}}\, \underline{\underline{M}}_f^{-1}\, \underline{\underline{A}}\, \underline{p}_s - \rho c \underline{\underline{A}}\underline{\dot{u}}_I = \rho c A \underline{\ddot{x}} \tag{2-7}$$

Equation (2-7) has been left in its current form rather than its implementation form, equation (2-1), to illustrate the fundamental concept of the DAA. In the DAA the total structural motion, $\underline{\ddot{x}}$, is assumed to generate two components of scattered pressure. This is a different result than one would get by assuming the two components of scattered pressure to additively drive the structure. An alternative derivation of the DAA has been given by Fellipa [12]

based on the mathematical theory of "matched asymptotic expansions" [13]. This derivation is very neat and incisive but for the current work where it is desired to make physically consistent simplifications of the DAA, it was felt that the above derivation gave more physical insight.

Referring back to equations (2-1) and (2-2) as the basic equations for the application of the DAA, one can see that in the form given by equation (2-1), the PWA contribution to the DAA and the VMA contribution to the DAA must be defined with the same level of spatial discretization. This is unfortunate since the radiation damping term, $\underline{p}_s = \rho c\,(\dot{\underline{x}}-\underline{u}_I)$, is a purely local approximation while the added mass term, $\underline{p}_s = \underline{\underline{M}}_f\,(\ddot{\underline{x}}-\dot{\underline{u}}_I)$, is complete coupled via the fully dense added mass matrix $\underline{\underline{M}}_f$. An interesting approach for creating a "banded added mass matrix" has been developed by Harten and Efrony [14]. Their approach involved the evaluation of the added mass matrix on subregions, with gradients as coupling variables on the boundaries of the subregions. Thus while the size of the resulting matrix is increased, the matrix becomes banded and the total number of arithmetic operations in a matrix multiplication or forward elimination-back substitution operation is reduced. The development in [14] was for bounded regions. When the method is extended to infinite regions, the integrals which must be evaluated for the added mass matrix become complex and very cumbersome and their accurate evaluation is computationally very time consuming. Because it was desired to have a computationally simplified DAA which could be implemented in a short time for the analysis of the ISM-A4 test, the banded added mass concept outlined in [14] was rejected for the present effort. However, the approach does appear promising and should be considered in the future.

The DAA formulation embodied by equations (2-1) and (2-2) directly couples the radiation damping and virtual mass contributions. If the DAA equations could be reformulated to separate these terms, many avenues for computational simplifications would be available. A procedure for accomplishing this is now outlined. If q is defined as the time integral of the scattered pressure, i.e., $\dot{q} = p_s$, then equation (2-1) yields after integrating and assuming zero initial conditions

$$\dot{\underline{q}} = \rho c\,(\dot{\underline{x}} - \underline{u}_I) - \rho c\,\underline{\underline{M}}_f^{-1}\,\underline{\underline{A}}\,\underline{q} \qquad (2\text{-}8)$$

If equation (2-8) is substituted for $\underline{p}_s$ in equation (2-2) a modified structural response equation of the form

$$\begin{aligned} M \ddot{\underline{x}} + \rho c A \dot{\underline{x}} + K \underline{x} &= - A \underline{p}_i \\ &+ \rho c \underline{A} \underline{u}_I + \rho c A M_f^{-1} A \underline{q} \end{aligned} \tag{2-9}$$

is obtained. Equations (2-8) and (2-9) form the modified DAA equation system which we chose to work with. This form of the DAA has been termed the pressure integral extrapolation method (PIE) by Park, Fellippa, and DeRuntz [15], since the coupling of the structural and fluid equations is via the integral of the scattered pressure, $\underline{q}$, and the structural velocity, $\dot{\underline{x}}$. The PIE form of the DAA equations has been shown to have better numerical stability characteristics than the standard form of the DAA, equations (2-1) and (2-2), [7].

In developing computationally simplified forms of equations (2-8) and (2-9) it is important to understand both the spatial and temporal significance of the terms in the DAA. The early time asymptote of the DAA is the PWA. As was previously discussed, the PWA is a local approximation in that the scattered pressure at a point is a function only of the velocity at the point. In contrast, the late time asymptote of the DAA, the VMA is a fully coupled approximation, so that motion at one point instantaneously generates a pressure everywhere on the structure. In attempting to simplify the computational form of the DAA, it is useful to understand what is early time and what is late time. Unfortunately, the DAA equation provides no insight on this point. Huang [16] has published an exact solution for response of an elastic cylinder to stepwave excitation. Referring to Huang's results, both the mode 0 (hoop breathing) and mode 1 (rigid translation) response have reached steady state by about 3 to 4 diameter transit time of the acoustic wave. However, responses associated with modes ≤ 2 show very little decay out to 10 to 20 diameter transits. For the cylinder considered by Huang contributions from modes higher than 2 are negligible and the response is very close to its steady state asymptote by 5 transit times. Hence, one might use this as an upper bound for defining what constitutes late time in the DAA. That such an assumption is valid for cylinders with circumferential stiffness or mass variations is not clear. The bending associated with these modes would correspond

to modes 2 and above. Since these modes do not converge to non-oscillatory motion as rapidly as do the lower modes, late time for such geometries may correspond to times far greater than 5 transit times.

In simplifying the added mass (late time) contribution to the DAA, two limiting cases can be considered. At early times but after significant structural response has developed, the incompressible flow field near a point is most likely due primarily to the local source corresponding to the structural motion at that point and a diagonal added mass matrix could be used. At very late times after all significant structural motion has decayed to negligible values, the added mass contribution for the mode 1 response could be applied. Referring back to the results of Huang [16], one might expect the diagonal added mass approach to work best for problems where higher order flexural modes contributed significantly to the response and the mode 1 added mass approach to work best for "clean" cylinder problems dominated by response in modes ≤ 2.

For simplicity, we will refer to the diagonal added mass approach as the "early late time" (ELT) DAA and the mode 1 added mass approach as the "late late time" (L^2T) DAA. For the ELT-DAA, equation (2-8) can be written for each nodal point independently as

$$\dot{q} + \rho c \, m_f \, a \, q = \rho c \, (\dot{x}^n - u_I^n). \qquad (2\text{-}10)$$

The L^2T-DAA for a two-dimensional problem reduces to

$$\dot{q} + \frac{2c}{a} q = c \, (\dot{u}_1 - \dot{u}_{1i}) \qquad (2\text{-}11)$$

where a is the radius of the cylinder and the subscript 1 refers to the mode 1 fourier decomposition of the quantity. In a like manner intermediate approaches which combined two or more added mass modes while retaining the exact plane wave characterization could be developed. Before proceeding along this line, the accuracy of the two simple approaches will be considered.

3. EVALUATION OF SIMPLIFIED DAA FORMS

The ranges of applicability of the ELT and L^2T simplifications of the DAA were implicitly evaluated in the previous chapter. The nature of the DAA equations precludes an explicit mathematical evaluation of their accuracy except on a problem specific basis. Such an evaluation will now be presented. In order to have names with better physical connotation, the ELT-DAA will be referred to as the plane wave-added mass (PWAM) plate approximation. The L^2T-DAA will be referred to as the PWAM cylinder approximation. Both formulations have been implemented into the STAGS code through the UPRESS subroutine.

The first example to be considered is the step wave response of a linearly elastic cylinder. The previously discussed exact solution due to Huang is used as a basis for comparison. Since this problem is dominated by mode 0 membrane and mode 1 translation, with very little bending, a comparison is made with the PWAM cylinder approximation. To illustrate the influence of the added mass effect the plane wave solution is also included. Figures 2-4 show the radial velocity of the cylinder at 0°, 90°, and 180°. The cylinder considered has a radius of 60 inches so that 2.0 msec corresponds to a diameter transit time of the shock wave in the fluid across the shell. Referring to Figures 2 and 4, one can see the early time, < 2 msec, effect of using only the mode 1 added mass effect. At 0° the velocity lags the exact solution while at 180° the velocity leads the exact solution. This is because of the instantaneous smearing of the added mass pressure to conform to a mode 1 translational response. Hence, high early time acceleration at the front side of the shell due to the incident wave gets partially smeared into a rigid body acceleration in the DAA calculation. At 90°, Figure 3, the agreement is excellent except for the pronounced overshoot in the radial velocity after the first peak. As can be seen the plane wave approximation also exhibits this rebound overshoot. As will be shown later, this overshoot is seen in full DAA solutions also. Hoop strains at 0°, 45°, and 90° are shown in Figures 5-7. The curves for Huang's exact solution are membrane values only. As was previously discussed and is illustrated by the comparisons, a mode 0, uniform circumferentially, membrane hoop strain dominates the deformation. What is interesting is that while the PWA does poorly on matching velocities, it does fairly well on matching the strains. This is

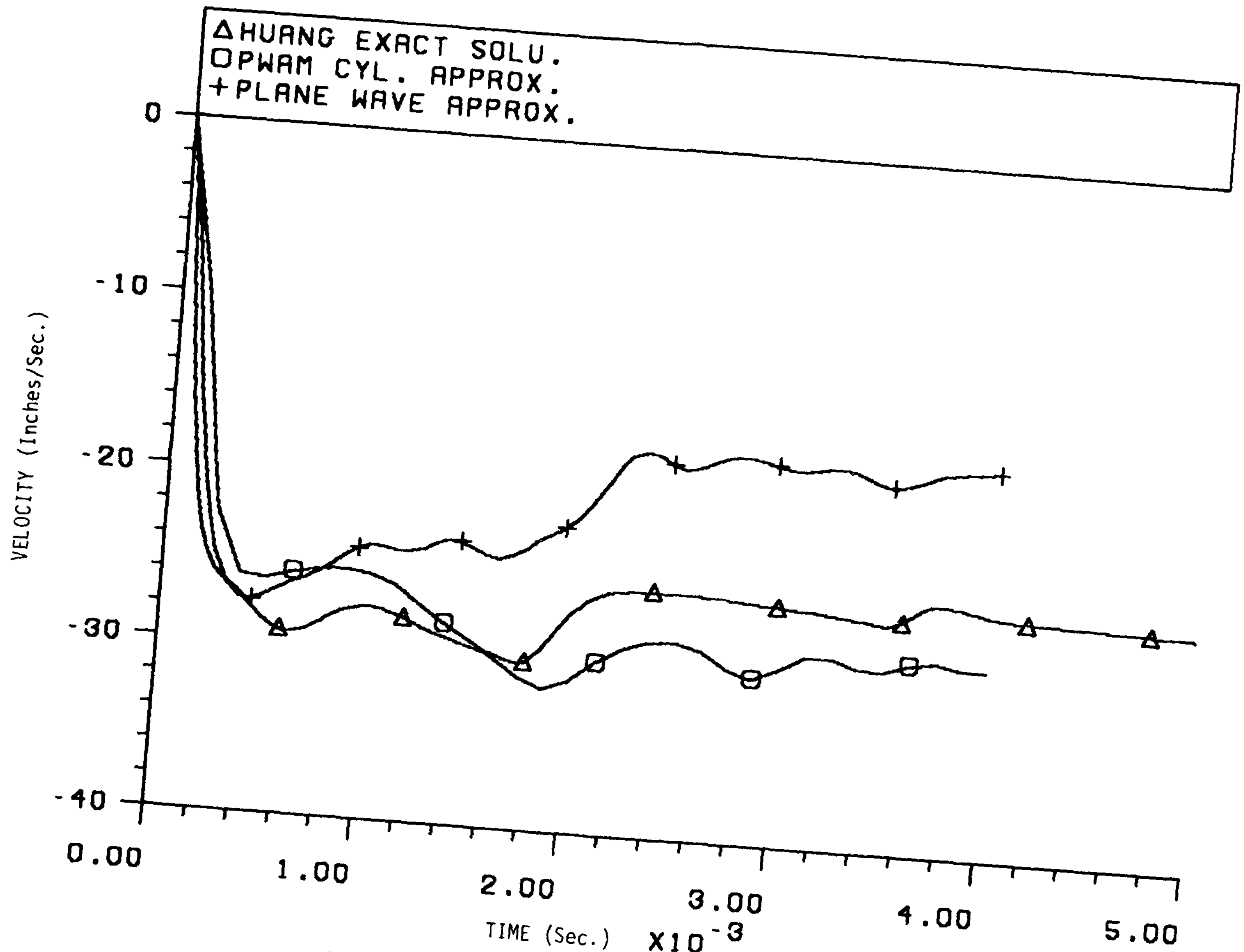

Figure 2. Elastic Cylinder - Velocity vs Time at 0°

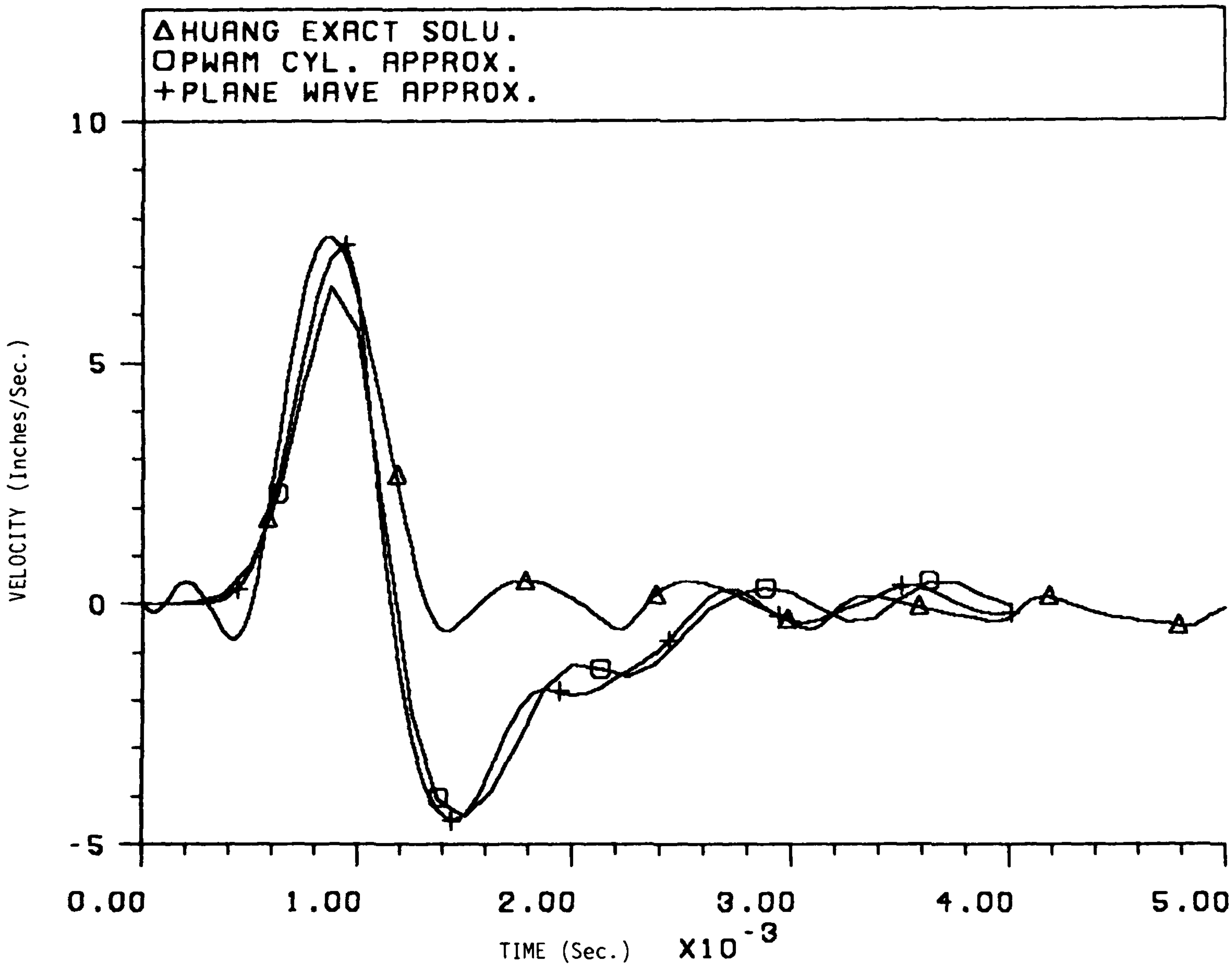

Figure 3. Elastic Cylinder - Velocity vs Time at 90°

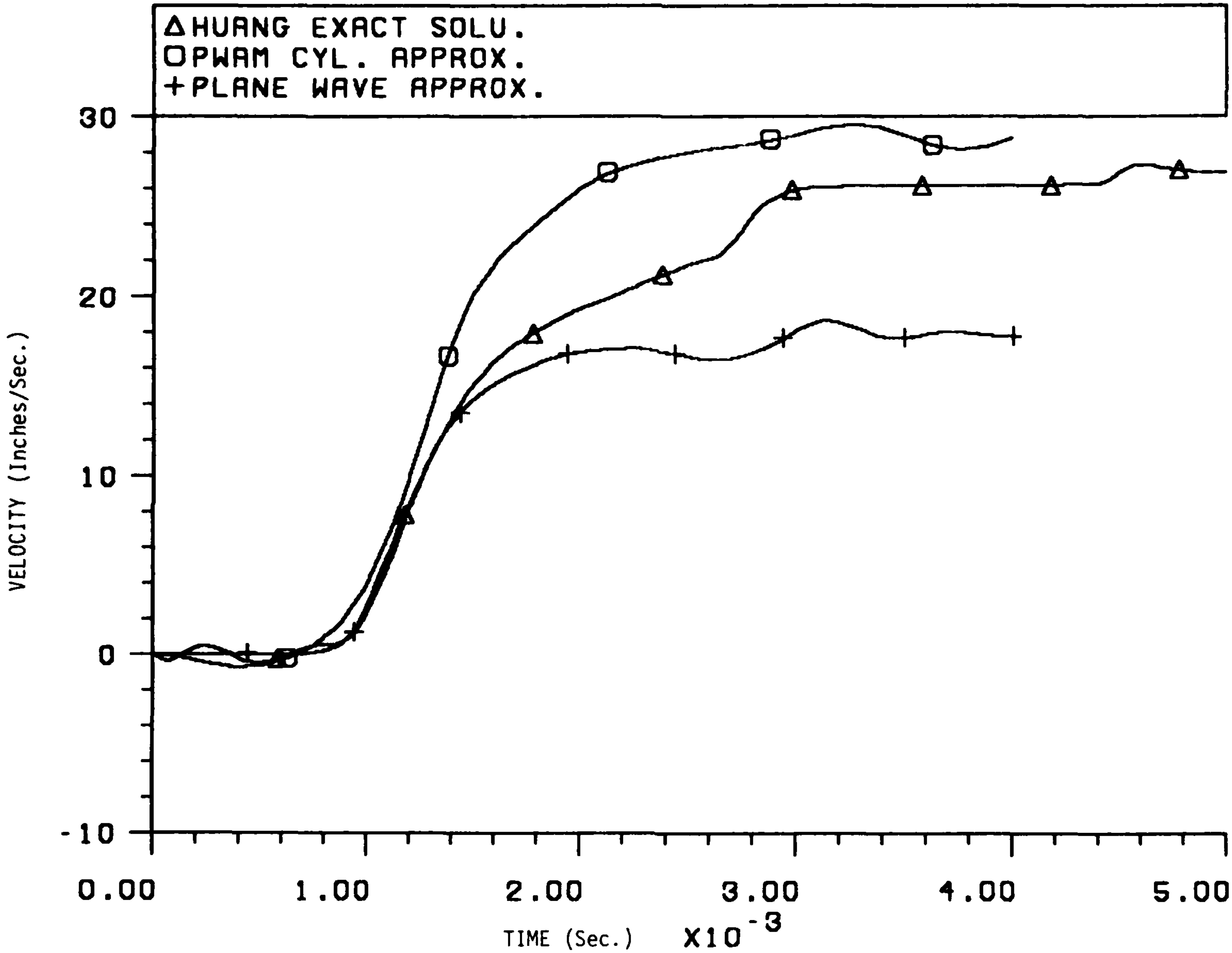

Figure 4. Elastic Cylinder - Velocity vs Time at 180°

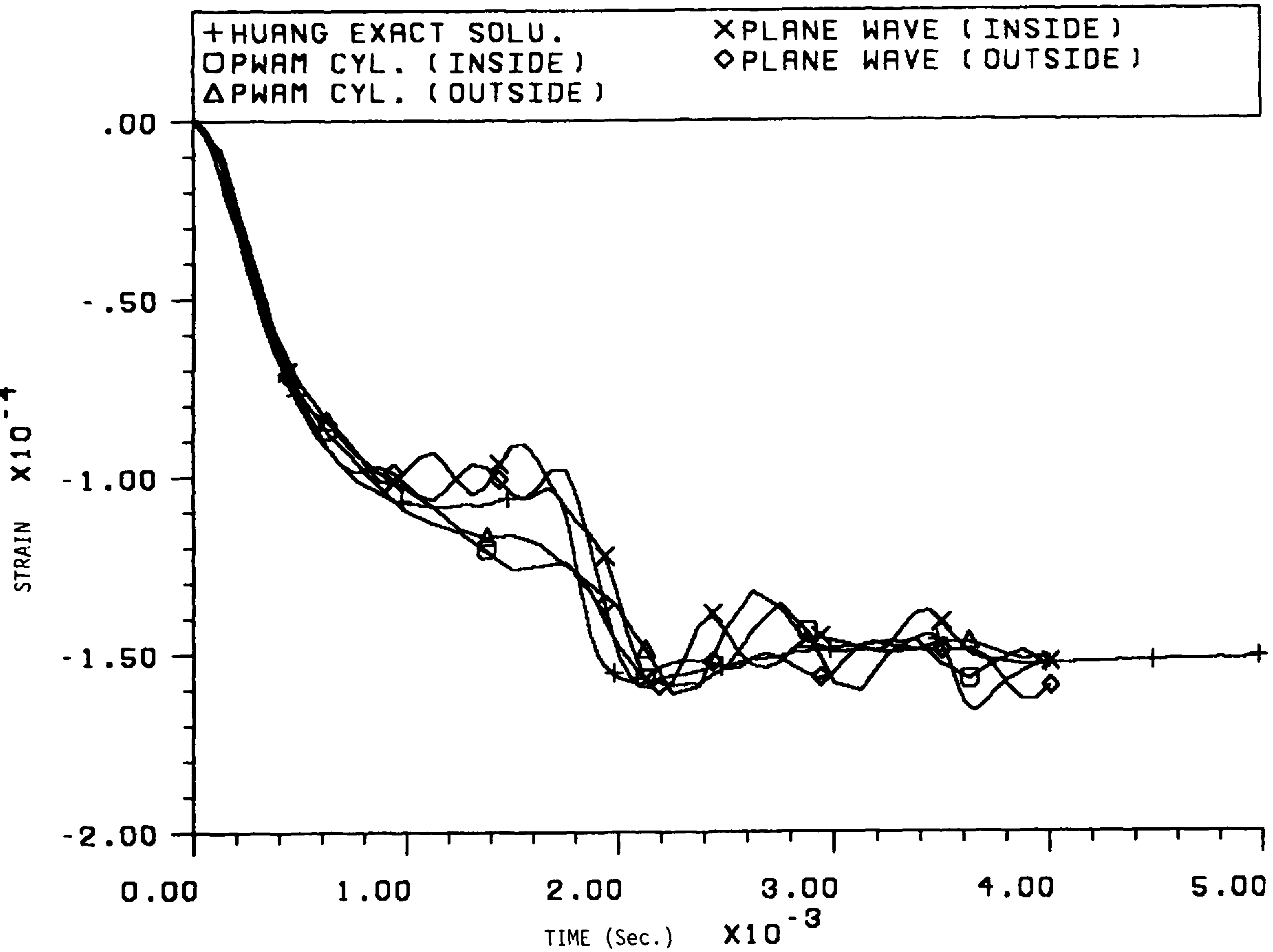

Figure 5. Elastic Cylinder - Strain vs Time at 0°

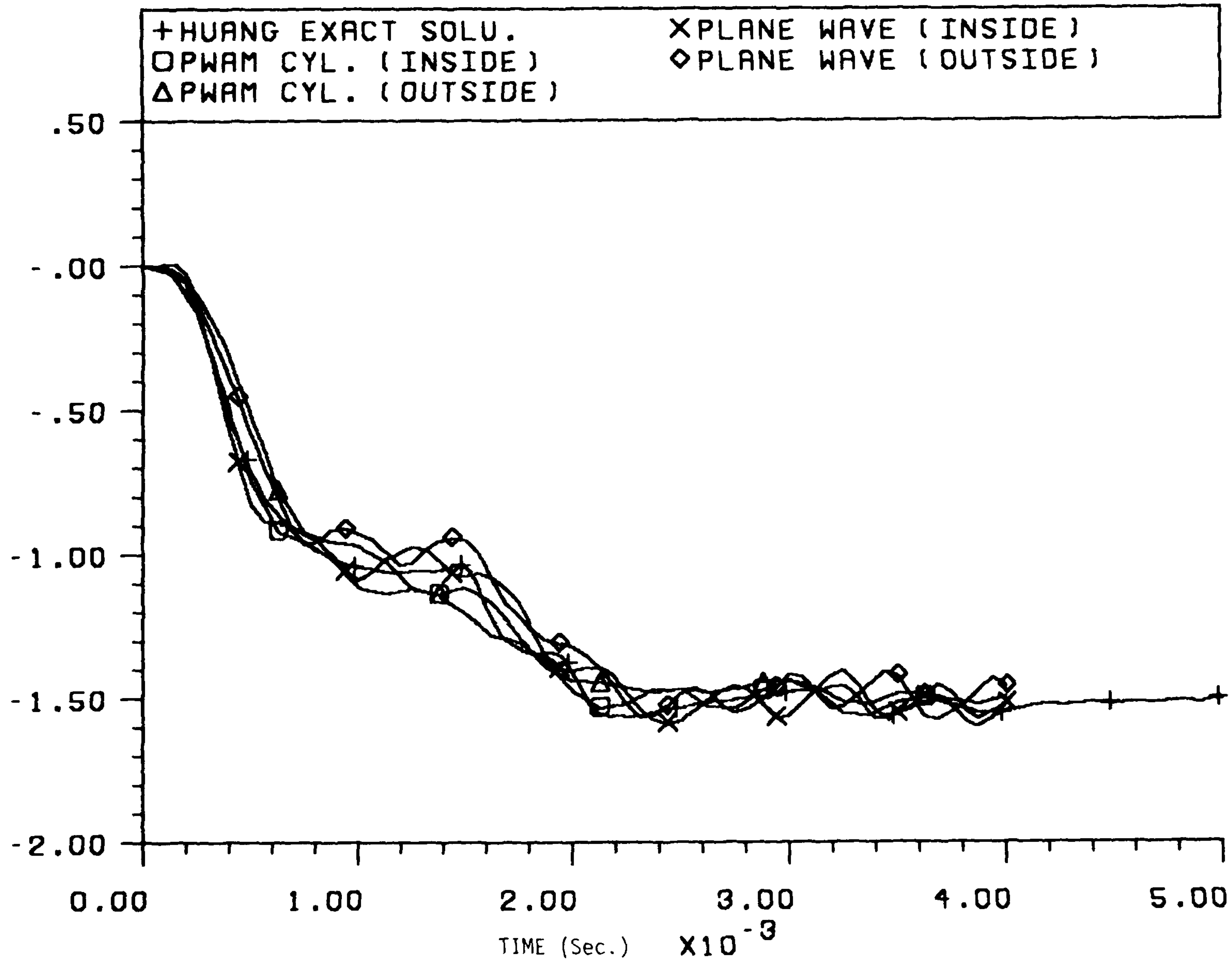

Figure 6. Elastic Cylinder - Strain vs Time at 90°

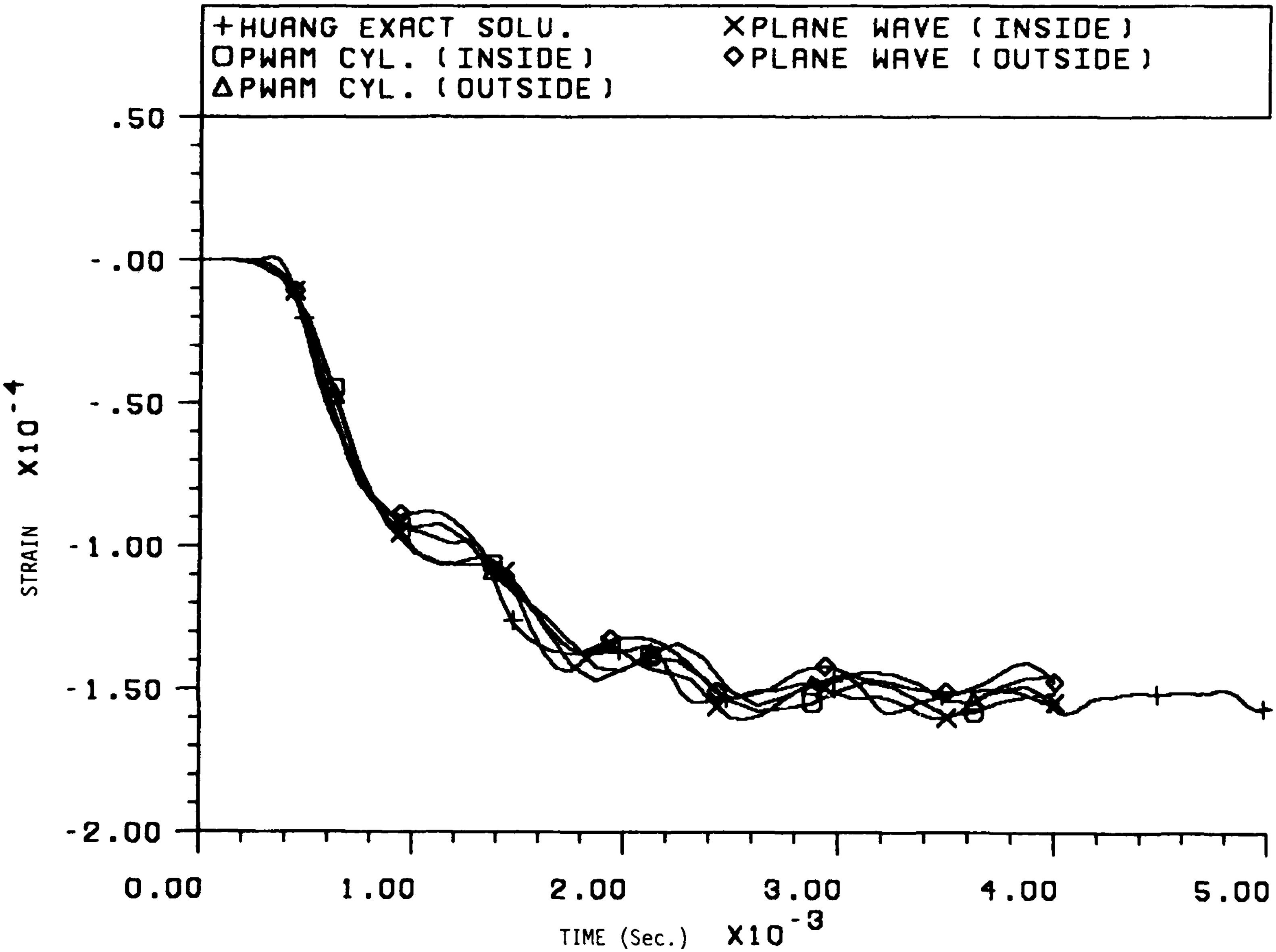

Figure 7. Elastic Cylinder - Strain vs Time at 180°

because for two-dimensional problems a mode 0 virtual mass solution does not exist [17], so that the DAA solutions converge to a PWA for the mode 0 solution of a cylinder in two dimensions.

In order to evaluate the accuracy of the approximations in a problem where flexure was significant, the previous problem was modified by inserting a flat plate attached to the cylinder at 0° and 180°. Thus, the incident wave will now induce bending about the internal plate, in addition to translation through the water. Since no exact solution has been published for this problem, a comparison will be made to a USA-STAGS solution. Both plasticity and large deflection effects are included in the analyses. Radial velocities at 0°, 45°, 90°, and 180° are shown in Figures 8-11. The agreement between the full DAA solution and the two simplifications is excellent at 0° and 180°. However, because the plate connecting the shell at these points is very stiff, the response is essentially mode 1 translational velocity. At 45° a divergence is seen between the two PWAM solutions and the DAA solution. At 90° all three methods show different results. Comparing Figure 10 to Figure 3, one sees that whereas the PWAM cylinder method predicted a peak radial velocity at 90° of approximately 80% the exact value for the cylinder, the ratios of the PWAM cylinder method to USA peak radial velocities is approximately 0.5. In order to determine whether this discrepancy was due to the difference in the problems, an inherent inaccuracy of the DAA, or an error in the USA code, a new DAA code was formulated. Figure 12 shows the comparison between radial velocities at 90° from USA, dashed curve, and a new DAA code, solid curve. The exact solution predicts an initial peak of 99 inches per second and a time of first zero crossing of 2.05 milliseconds. From this we conclude that the error is in the USA code and that the PWAM responses shown in Figures 10 and 11 are valid approximations. In general, the PWAM plate approximation appears to more accurately pick up the early time response. The influence of the inaccurate velocities predicted by USA is shown in the strain comparisons in Figures 13-15. Figure 14 shows the USA solution giving a peak bending strain approximately five times greater than the PWAM solutions.

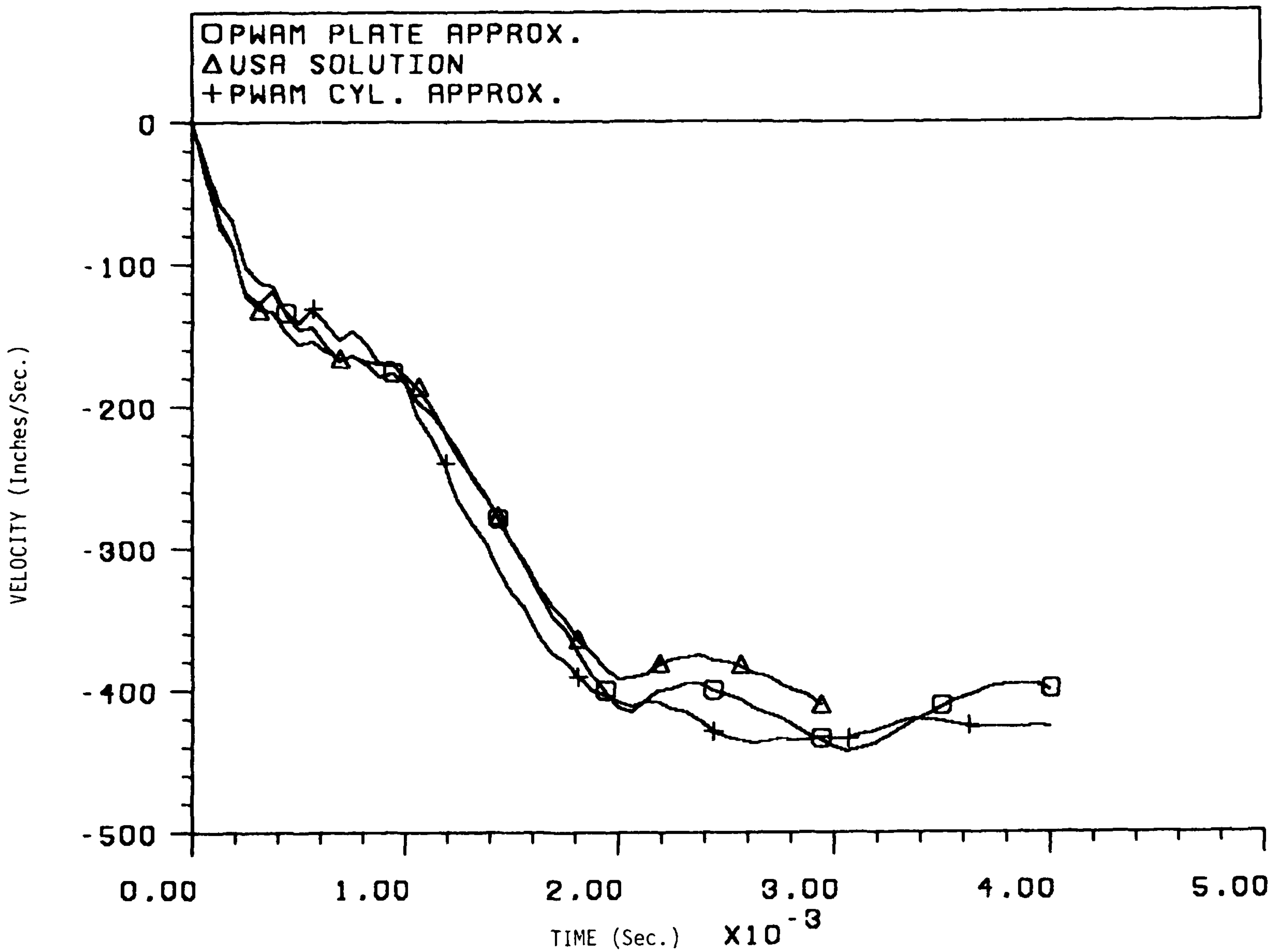

Figure 8. Nonlinear Cylinder with Internal Plate - Velocity vs Time at 0°

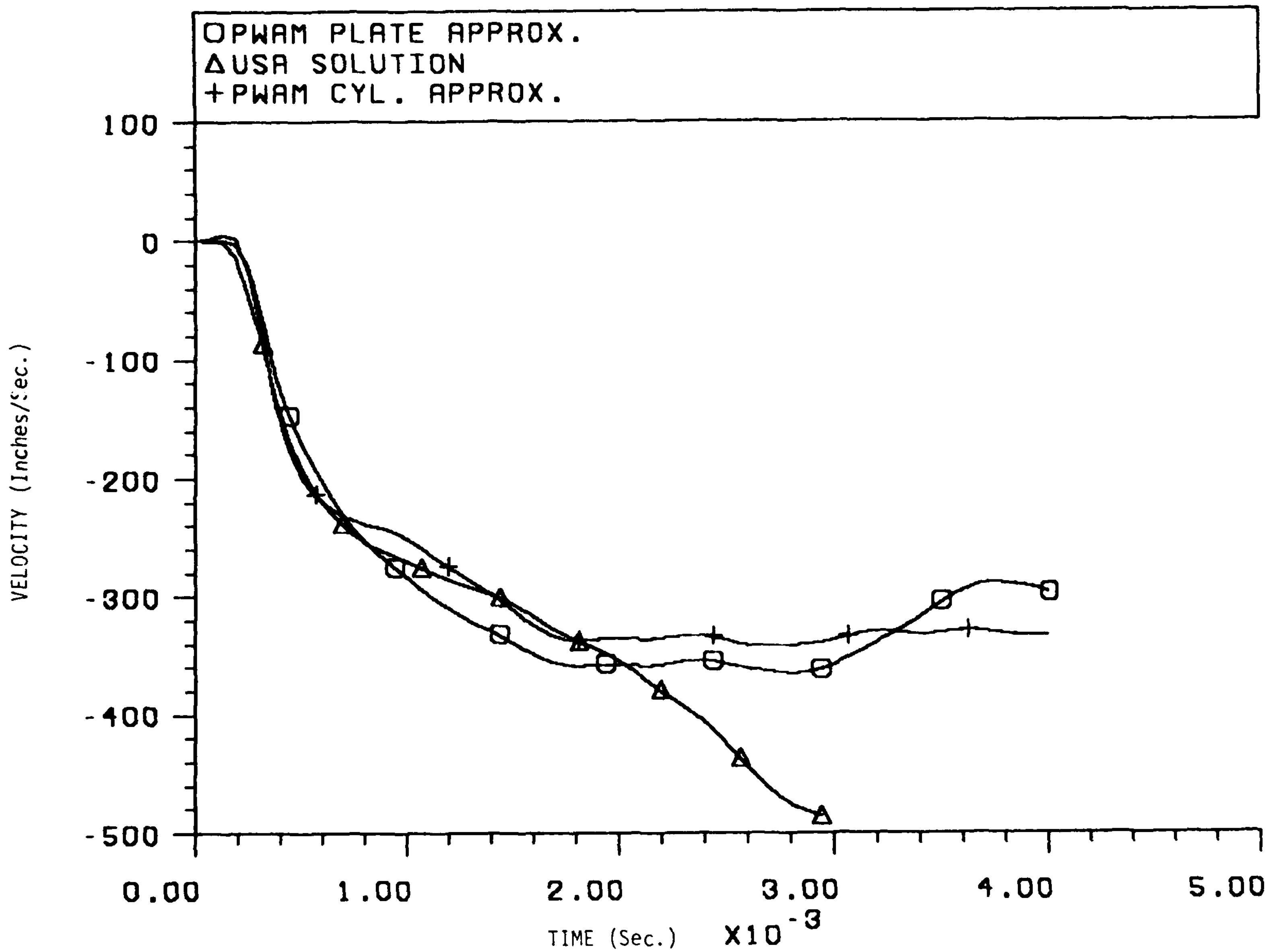

Figure 9. Nonlinear Cylinder with Internal Plate - Velocity vs Time at 45°

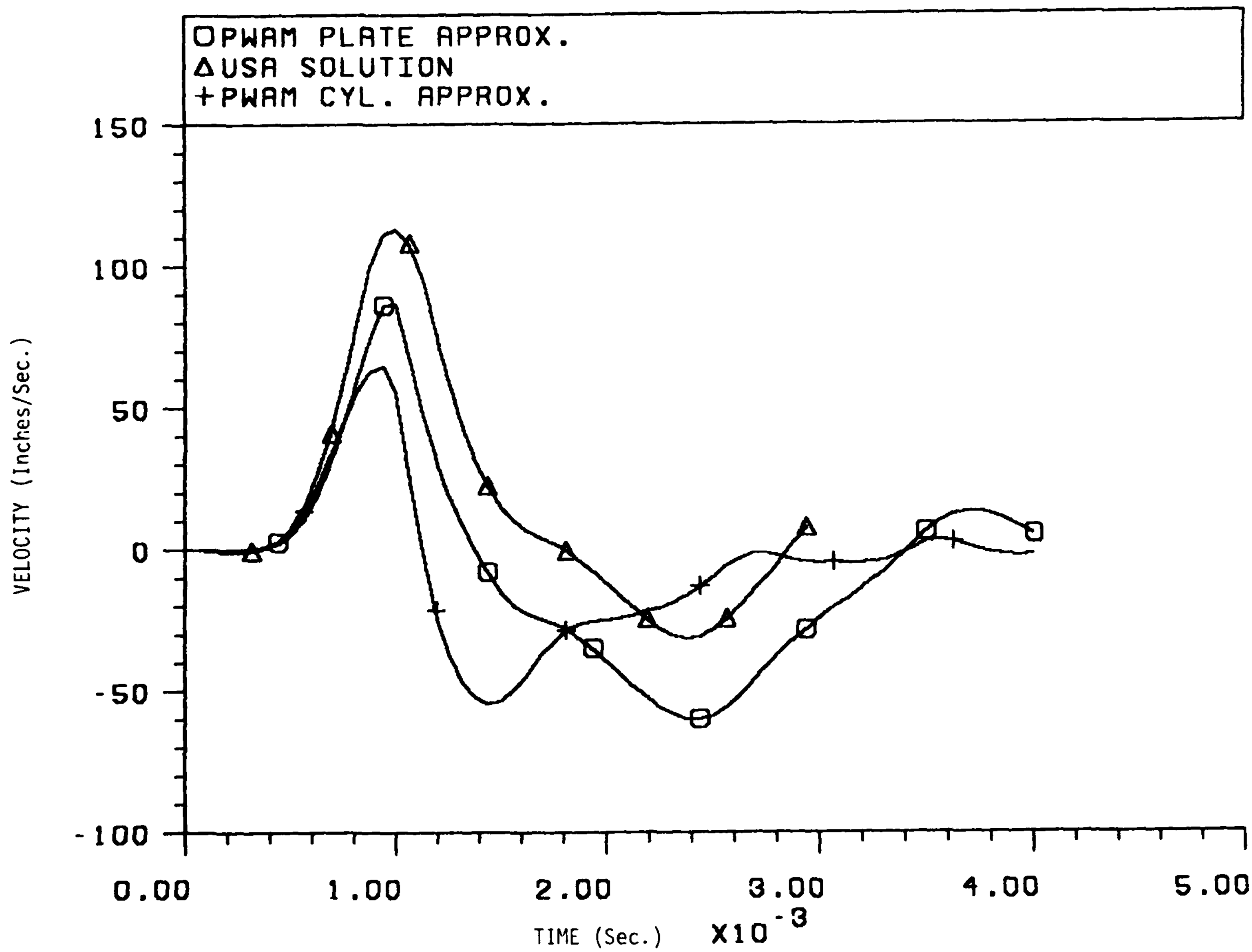

Figure 10. Nonlinear Cylinder with Internal Plate - Velocity vs Time at 90°

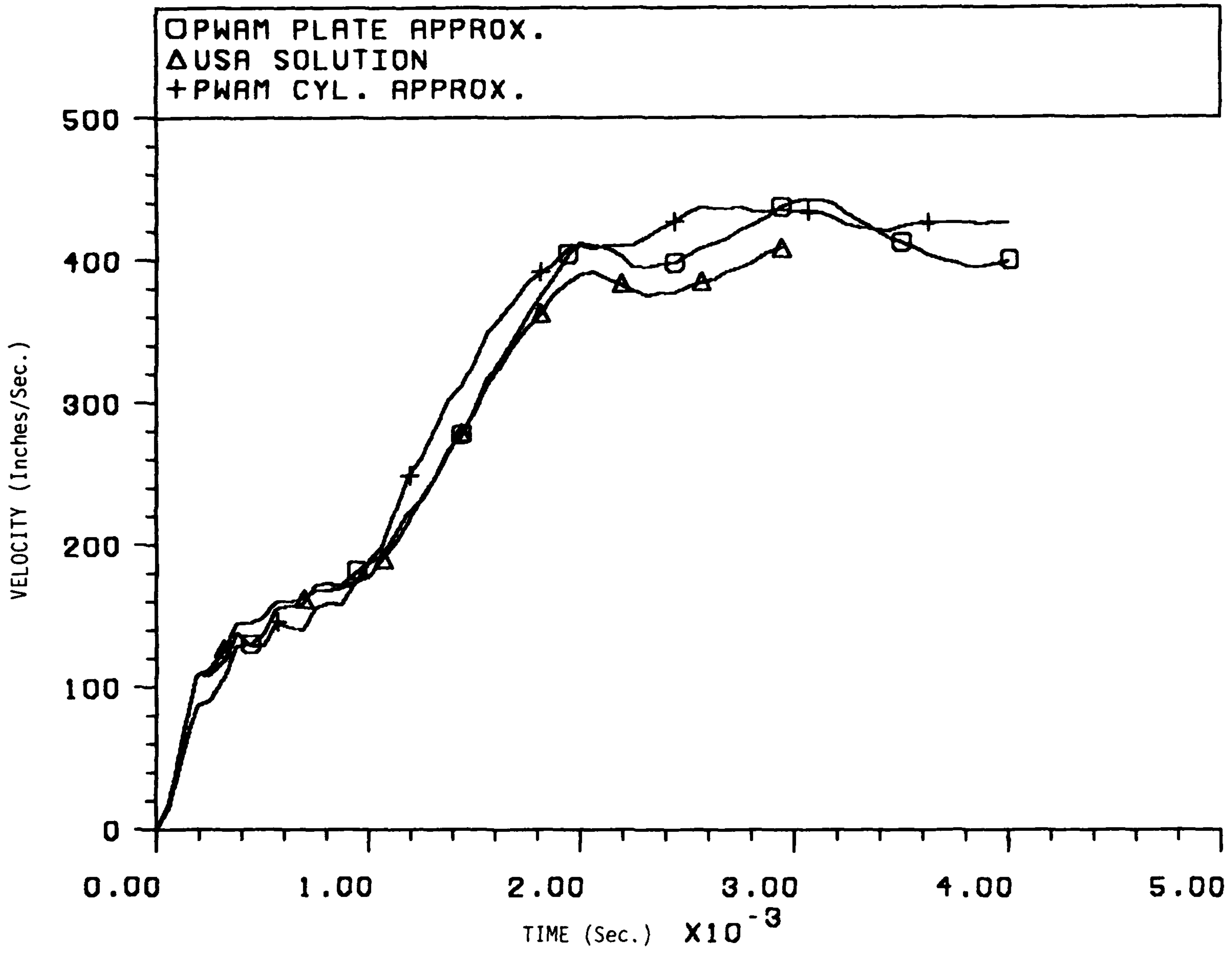

Figure 11. Nonlinear Cylinder with Internal Plate - Velocity vs Time at 180°

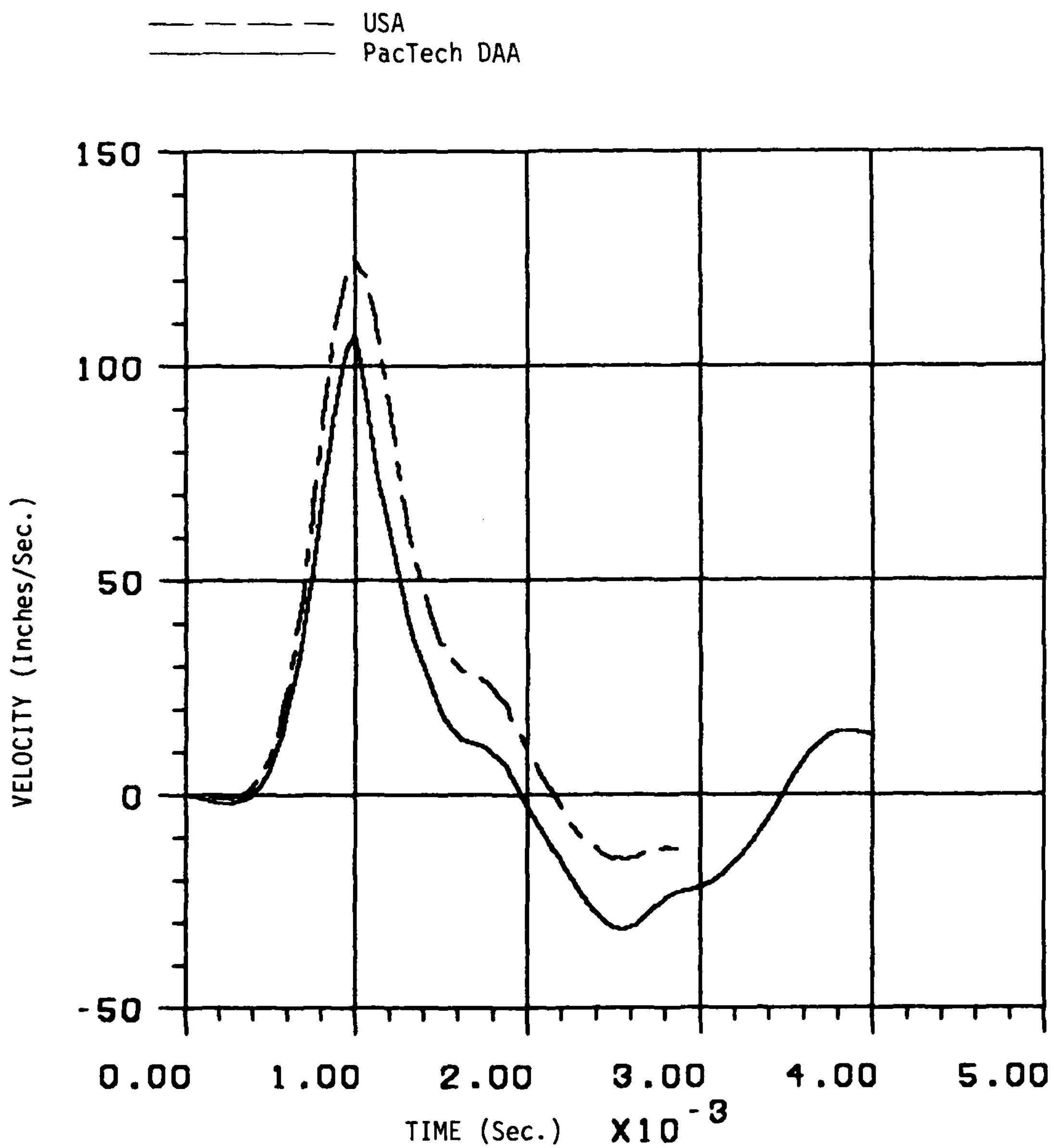

Figure 12. Comparison of Velocity at 90° From USA and PacTech DAA

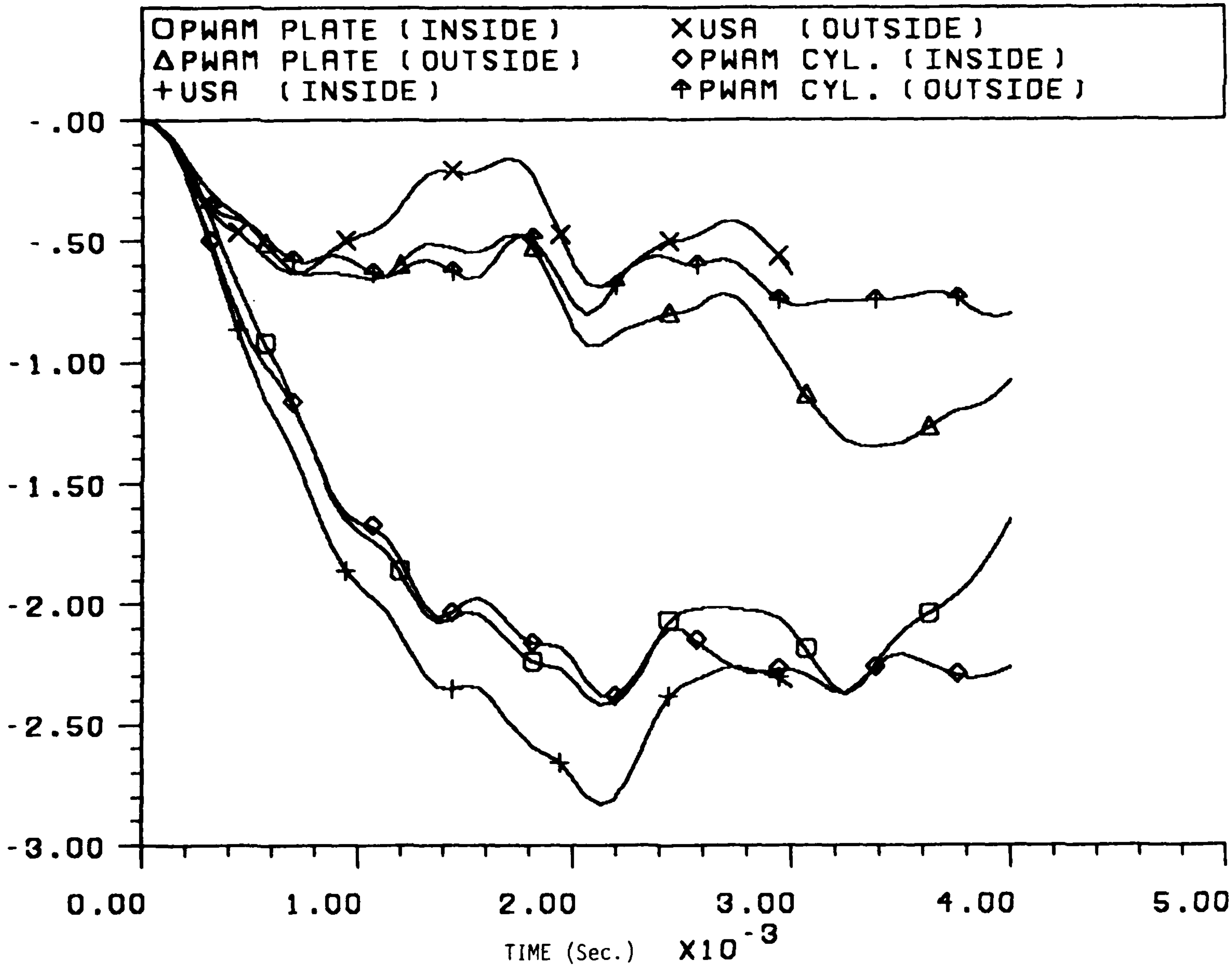

Figure 13. Nonlinear Cylinder With Internal Plate - Strain vs Time at 0°

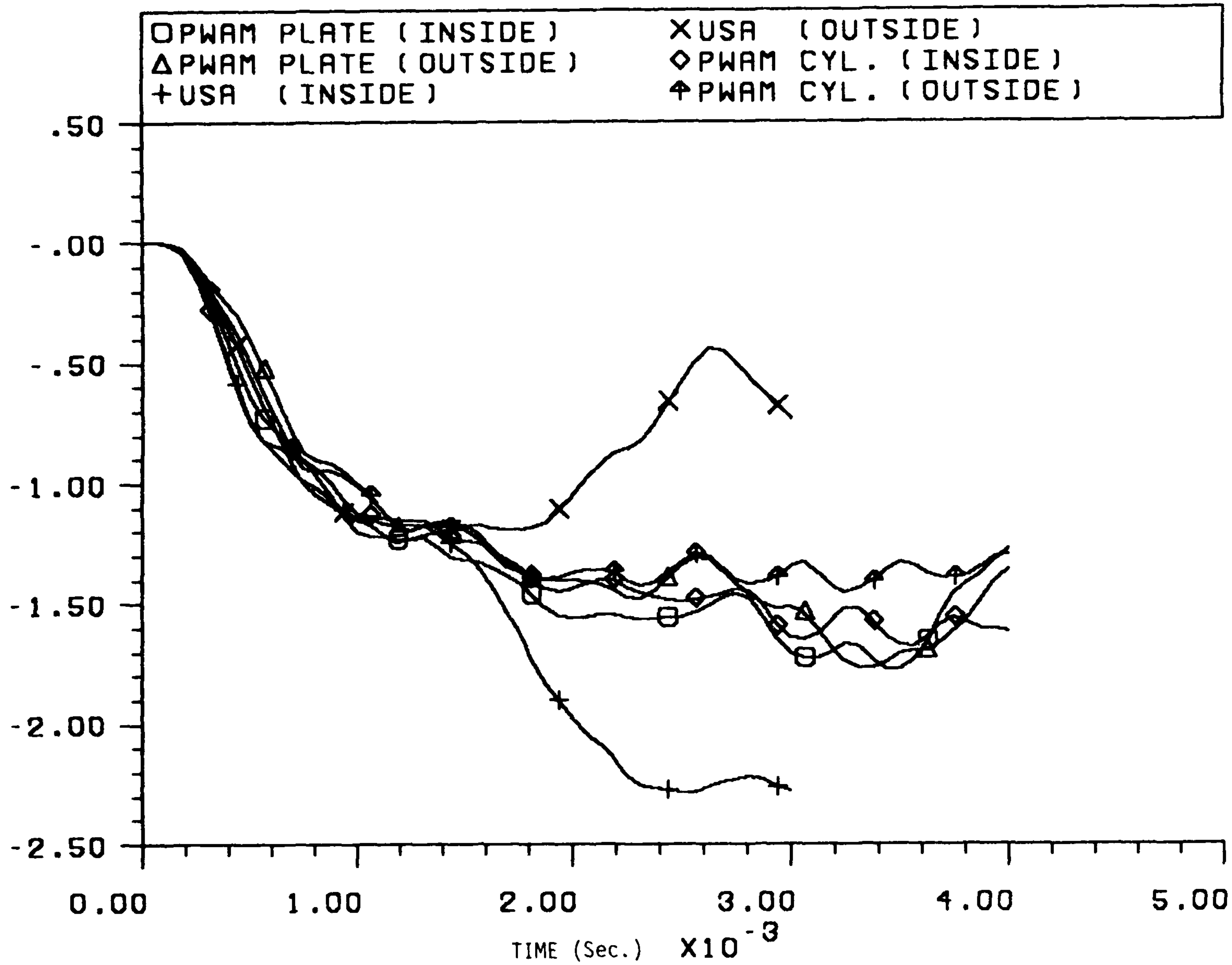

Figure 14. Nonlinear Cylinder With Internal Plate - Strain vs Time at 45°

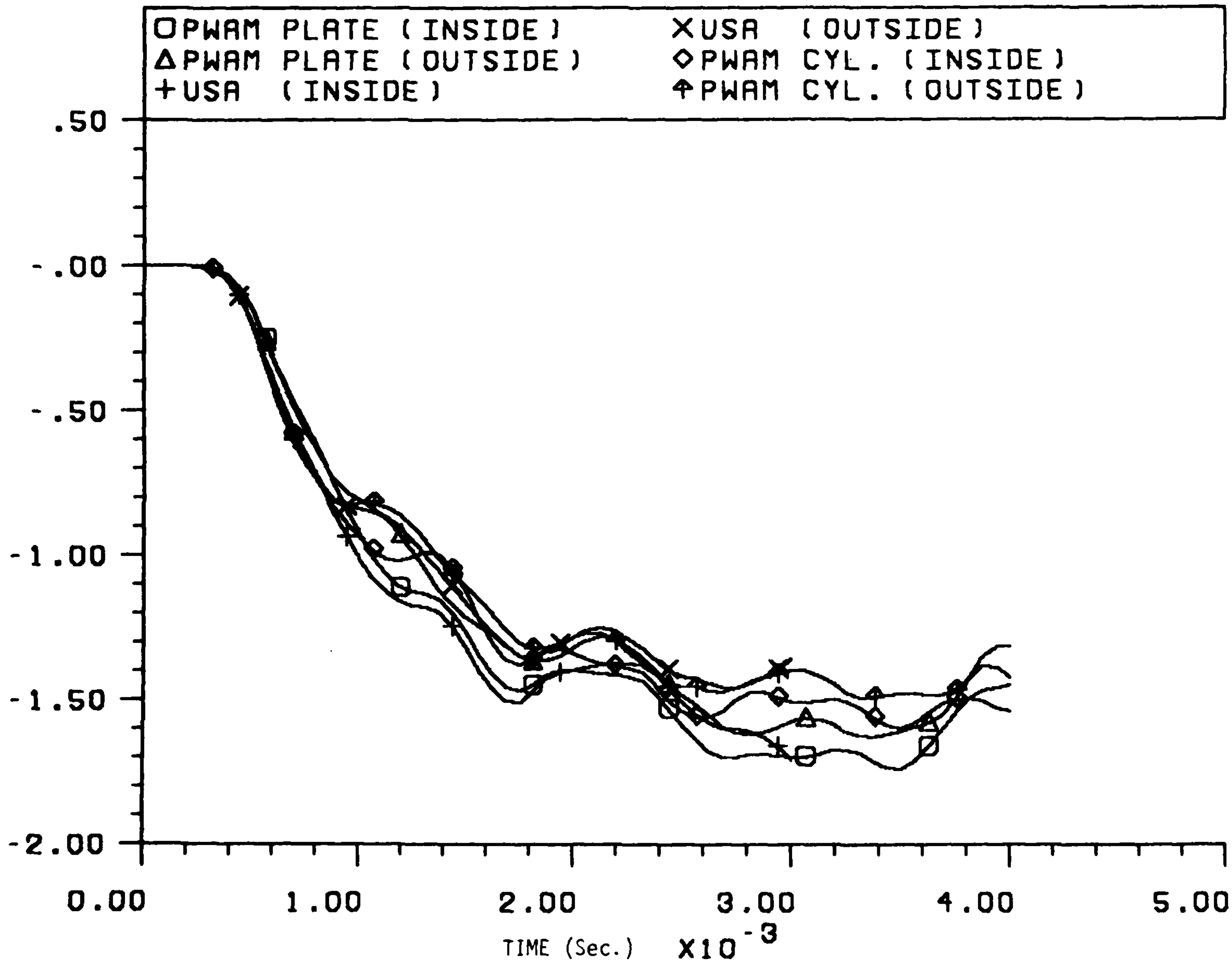

Figure 15. Nonlinear Cylinder With Internal Plate - Strain vs Time at 90°

4. SUMMARY AND CONCLUSIONS

In this report, options for reducing the computational complexity of the DAA have been examined. Two approaches, the PWAM plate approximation and the PWAM cylinder approximation, have been proposed. Based on a limited set of comparison calculations, both approaches look very promising for applications where very refined structural meshes are required. For applications to three-dimensional structures, the PWAM cylinder approximation is applied to each ring of elements independently, using the two-dimensional added mass modified for three-dimensional effects as shown in Lamb [18]. This axial decoupling of the added mass effects is consistent with the experimental results of Chertock [10] and the approach used by Hicks for whipping calculations[11]. The mathematical form of the PWAM plate approximation is similar to the curved wave approximation (CWA) of Haywood [19]. Where PWAM is based on a local added mass effect to represent resultant fluid flow due to structural motion, the CWA represent the fluid flow as due to the net outflow (afterflow) from a diverging wave.

Both versions of PWAM appear satisfactory for the two-dimensional test problems, with the plate approximation performing slightly better. However, the only truly valid evaluation is a comparison of their ability to replicate the experimental results from a test on a complex three-dimensional structure. In Volume II of this report, such an evaluation is made for the ISM-A4 test. A more definitive appraisal of the two PWAM approaches is reserved for that report.

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